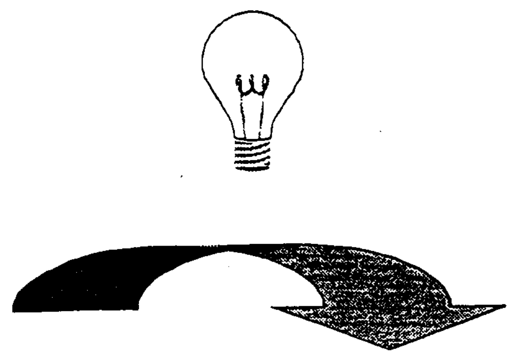
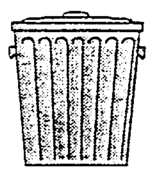
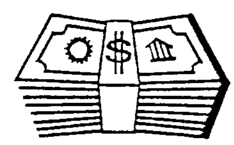




TRASH TO CASH



Yolo County
Controlled Landfill Bioreactor Project

Accelerating Landfill Gas Generation for Energy Production

Towards a Twentieth Century Landfill

A Project of the Public Technology, Inc. Energy Program

YOLO COUNTY, CALIFORNIA

TRASH TO CASH

CONTROLLED LANDFILL BIOREACTOR PROJECT

URBAN CONSORTIUM
ENERGY TASK FORCE

Yolo County Division of Integrated
Waste Management

April 1998

Order No. 98/97-317

PUBLIC
TECHNOLOGY,
INC.

URBAN CONSORTIUM

Background

URBAN CONSORTIUM

Public Technology, Inc. (PTI), is the non-profit technology organization of the National League of Cities (NLC), the National Association of Counties (NACo), and the International City/County Management Association (ICMA). PTI's mission is to bring technology to local governments. Through collective research and development efforts in its member jurisdictions, PTI creates and advances technology-based products, services, and enterprises for all cities and counties.

Four active task forces, each composed of members of PTI's Urban Consortium (UC)—which represents fifty of the nation's largest and most progressive cities and urban counties—drive PTI's research and commercialization efforts. One of these task forces is the Urban Consortium Energy Task Force (UCETF), which was established to address critical energy needs of urban America.

THE URBAN CONSORTIUM ENERGY TASK FORCE

The UCETF is the nation's most extensive cooperative local government program to improve energy management and technology applications in local governments. Its membership is composed of local government officials from America's large urban centers. The four major goals established by UCETF members are to:

1. Pursue collaborative solutions to interrelated energy, environment and economic development issues at the local level;
2. Improve energy efficiency, reduce costs and develop revenue from local energy assets;
3. Promote practices and efforts at the local level to assure that energy and environmental considerations are broadly integrated into local decision-making, and to address the interrelationships between energy, environment and economic policies; and
4. Act as the implementation arm for NLC and NACo policies.

Under an annual program partly funded by the U.S. Department of Energy (USDOE), a number of city and county projects propose to meet UCETF objectives. Projects selected for each year's program are organized in thematic units, such as Utilities/Buildings, Transportation, Sustainable Communities, and Technology Transfer, to assure effective management and ongoing peer-to-peer exchanges. The results of these research projects are documented in reports such as this one, and made available for broad dissemination among other local governments through PTI.

The research and studies described in this report were made possible by grants from the MUNICIPAL ENERGY MANAGEMENT program of the Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy.

PUBLIC TECHNOLOGY, INC.

1301 Pennsylvania Ave., NW
Washington, DC 20004-1793
202.626.2400
800.852.4934
FAX 202.626.2498
INTERNET http://pti.nw.dc.us

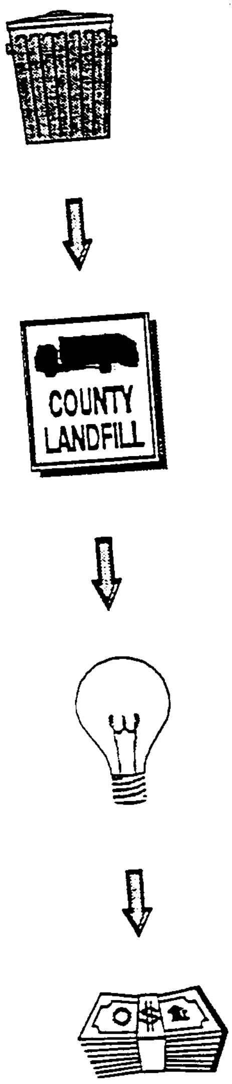


Table of Contents

Prepared by:

Yolo County Division of Integrated Waste Management, Davis, California
Ramin Yazdani, P.E.
Rick Moore, P.E.
Karina Dahl

Institute for Environmental Management, Palo Alto, California
Don Augenstein, P.E.

i. Acknowledgments

Yolo County wishes to acknowledge the contributions and efforts of the following individuals and organizations who have made the Yolo County Controlled Landfill Project a success. The project would have never begun without the financial support for the construction phase of the project from the California Energy Commission (CEC), Sacramento County, and the California Integrated Waste Management Board. The support of Dara Salour, the CEC Project Manager, is greatly appreciated. The monitoring phase of the project has been funded through financial assistance from the U. S. Department of Energy through the Urban Consortium Energy Task Force (UCETF) and the Western Regional Biomass Energy Program (WRBEP).

The helpfulness and guidance of Larry Blackstad, our UCETF Project Manager, and Evan Hughes, of the Electric Power Research Institute, our WRBEP Project Manager, are acknowledged with appreciation.

The kindness and responsiveness of Linda Davis, UCETF Business Officer, has been greatly appreciated. Thanks also goes to the staff of Public Technology, Inc., who are always there when we need them.

Larry Riegert, currently with HCW-L Engineers in Wenatchee, Washington, is acknowledged for having conducted the initial feasibility study while working at Yolo County that led the county to pursue research of this technology. Dr. Samual A. Hart, former professor of agricultural engineering at the University of California, Davis, is acknowledged for having prepared the first proposal to the CEC which went unfunded.

EMCON Associates supported the preparation of the CEC proposal that received the initial funding which led to the realization of this project.

Don Augenstein of the Institute for Environmental Management (IEM) of Palo Alto, prepared the second and third proposals to the CEC while at EMCON, the third of which received funding. He has provided valuable insights and support throughout, including preparation of this report. Mr. Augenstein's on-going technical guidance and enthusiasm have been instrumental to the success of the project.

The assistance and technical support of John Pacey of EMCON/FHC corporation during the design and planning phase of the project has been a great benefit.

ATEEM Electrical Engineers of Sacramento was instrumental to the success of the data acquisition system.

B & D Geerts General Contractors contributed immensely to the construction and maintenance of the project.

Polyflex, Inc. is acknowledged for providing materials to the project at a reduced price.

The ongoing support of the Yolo County Board of Supervisors has been essential to the success of the project.

Also acknowledged are the staff of Yolo County's Division of Integrated Waste Management, who's hard work and dedication have resulted in a project of which we can be proud.

I. Executive Summary

There is something new going on at Yolo County Central Landfill that could change the direction of solid waste management. Yolo County is operating a landfill as a biological waste treatment system, in a process termed "controlled landfilling". The objective of the project is to reduce the adverse effects of slow waste decomposition associated with current landfill practices. Through controlled landfilling, the waste decomposition is controlled and accelerated, with waste decomposition and stabilization completed much more rapidly than in common landfill practices with near-complete capture of landfill gas. With current "conventional" landfilling practice waste decomposes slowly, over time spans of several decades, producing landfill gas as a by-product. Landfill gas is primarily a mixture of methane (CH_4) and carbon dioxide (CO_2), both of which are greenhouse gases, with methane being many times more potent than carbon dioxide as a greenhouse gas. Methane is also a fuel, and this by-product of landfill decomposition creates a substantial energy resource. With controlled landfilling, maximum renewable energy can be recovered for electricity or other uses, in addition to a myriad of other benefits including significant climate and other environmental benefits.

Conventional landfill practices result in slow waste decomposition since regulations require that landfilled waste be kept as dry as possible; this has been referred to as "dry tomb" landfilling. Landfill surface liners in current use are effective in preventing liquid from entering the landfill and wetting the waste. However, this results in prolonging the decomposition process far into the future. Landfilled waste is required to be kept as dry as possible to minimize the potential for groundwater contamination. Current technology for protecting groundwater against contamination from landfills is to construct landfills with low permeability bottom liners and leachate collection systems. Leachate is the liquid that drains from garbage when liquid, usually rainfall, infiltrates the surface of the landfill and percolates through the waste. The low permeability bottom liners prevent the leachate from leaving the landfill and entering the groundwater. However, the integrity of these liner systems over the several decades that waste is decomposing in conventional landfills is unknown. Leachate produced from the slowly decomposing waste carries a high pollutant load that decreases dramatically after the waste has been decomposed. Dry tomb landfilling practices have been referred to as "ticking time bombs" because the waste decomposition rate will be slow until sometime in the future when the surface liner systems fail and the non-decomposed waste is wetted. By accelerating the decomposition rate by wetting landfilled waste, groundwater protection may actually be enhanced by decomposing the waste rapidly, while the protective liner systems are relatively new. Adding water to wet the waste, as is done in this project, is the simplest and most effective means to accelerate waste decomposition. Controlled landfilling would treat the waste in the near-term, rather then postponing the problem for future generations.

"Application of controlled landfilling to an additional 50% of waste landfilled in the US could provide about 270 billion cubic feet of methane."

"This amount of renewable methane energy would be equivalent to more than 100,000 barrels of oil per day."

The application of controlled landfilling technology results in substantial energy potential and climate benefits. Use of landfill gas for energy applications in the United States, principally electricity, is estimated by U. S. Environmental Protection Agency and others at about 10% of its potential. It is estimated that application of controlled landfilling technology to an additional 50% of the waste that is now landfilled in the United States could provide about 270 billion cubic feet of methane yearly, sufficient to supply about 1% of U. S. electric needs based on U. S. Department of Energy estimates. This amount of renewable methane energy would be equivalent to more than 100,000 barrels of oil per day. Displaced fossil fuel, or fossil fuel that has been replaced with landfill gas energy, would prevent the equivalent of about thirty million tons of fossil CO_2 carbon emissions. The approach will also reduce methane emissions associated with conventional landfilling, decreasing greenhouse gas emissions by an estimated 40 million metric tons per year. Landfill gas emissions mitigated by controlled landfilling are estimated to be among the least costly measures that may be taken to abate a component of the greenhouse problem, being equivalent to CO_2 abatement at costs of $1-5 per ton CO_2.

"By accelerating the decomposition rate by wetting landfilled waste, groundwater protection may actually be enhanced by decomposing the waste rapidly, while the environmental protective liner systems are relatively new."

Most important to the project objectives is showing that landfill methane generation and recovery can be greatly increased and fugitive emissions minimized. The enhanced demonstration cell is currently producing methane at a normalized rate which is about ten times higher than landfill methane recovery rates from conventional landfills. In fact, normalized methane recovery rates in the Yolo County enhanced cell are the highest documented from a large mass of waste anywhere in the world. At the same time, because of design and operational features, fugitive emissions to the atmosphere are close to nil.

In addition to energy and greenhouse gas mitigation benefits, controlled landfilling provides other important benefits to landfill operation. The rapid conversion of landfilled solid waste to gas creates additional space in the landfill that can be used to place additional waste when the landfill would otherwise have been full. Landfill life extensions amounting to 10-20% should be possible. In a conventional landfill, settlement that occurs from decomposition often comes too late to follow up with more landfilling, and instead becomes a maintenance problem after landfill closure.

Leachate management is also facilitated through controlled landfilling. The landfill can be used to equalize leachate flows while the landfill itself serves as a biological treatment system. Leachate pollutant levels are reduced by recirculating the leachate back through the waste. Rapid decomposition also reduces long-term maintenance costs because the problems associated with landfill gas and high pollution strength leachate over the long-term are minimized.

The construction phase of the project has been funded by two California Counties, Yolo and Sacramento Counties, the California Energy Commission, and the California Integrated Waste Management Board. More recent funding for the project's monitoring phase has come from the U. S. Department of Energy through the Urban Consortium Energy Task Force (UCETF) and the Western Regional Biomass Energy Program (WRBEP). The WRBEP grant is administered by the Electric Power Research Institute (EPRI) which is interested in the technology for both the renewable energy and climate benefits. Contractors have included D. Augenstein of the Institute for Environmental Management, located in Palo Alto, California, who has been active in the project since its inception. Other assistance has come from J. Pacey of FHC/EMCON Corporation, former CEO of EMCON Associates, an engineering consulting firm. EMCON Associates funded the preparation of the initial proposal funded by the California Energy Commission.

II. Concept and Conduct

This project grew out of a desire to develop better, more environmentally sound landfill management practices, and to make landfill gas-energy a more economical energy source. The following section describes conventional landfilling practices and why controlled landfilling is a better way to manage solid waste.

"Controlled landfilling renders projections of the landfill gas generation rate and yield much more reliable, which serves to improve the economics of landfill gas energy generation."

Controlled Landfilling

Controlled landfilling is the management of landfills as biological treatment systems where the decomposition processes are accelerated. The goal of the project is to show that landfilled waste can be decomposed in 5 to 10 years, rather than the several decades in conventional landfills. Accelerated decomposition is achieved by increasing the moisture content of the waste through liquid addition and leachate recirculation. In general, controlled landfilling should be applied to landfill modules designed for leachate recirculation. This requires modifications to the base liner system of traditional landfills to accommodate for the increased leachate flows. Besides design related issues, landfill operations will also be modified. Leachate management will be critical for optimal biological decomposition. Monitoring leachate quantities and quality will be necessary to assess the biological conditions within the landfill. To facilitate moisture distribution within the waste, alternative daily cover such as shredded greenwaste instead of soil may be a preferred material for intermediate cover. Active management of the gas collection system will also be necessary due to the accelerated gas generation. Benefits of controlled landfilling are outlined below and will be presented in detail in a later section.

Energy generation.

Controlled landfilling will shorten the time frame for landfill gas generation from several decades to within 10 years. This renders projections of the landfill gas generation rate and yield much more reliable, which serves to improve the economics of landfill gas energy generation. Qualitative landfill gas generation curves for controlled and conventional landfilling are shown in Figure 1 to illustrate the concept of accelerated landfill decomposition.

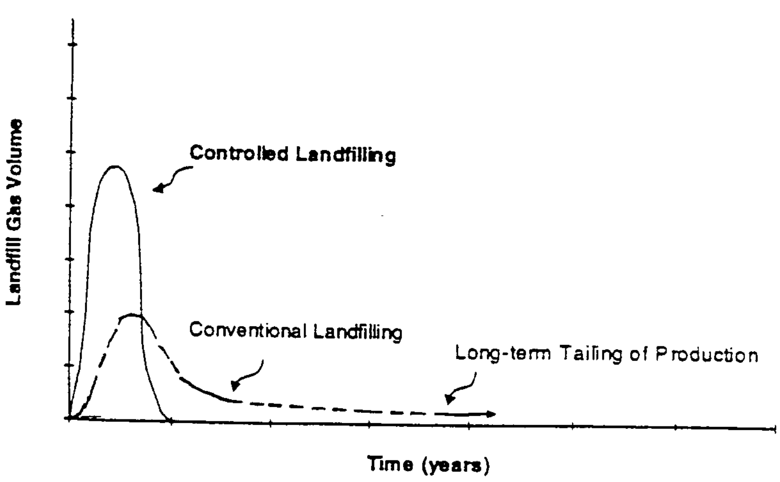


Figure 1. Landfill Gas Generation from Controlled and Conventional Landfilling Conceptual Illustration

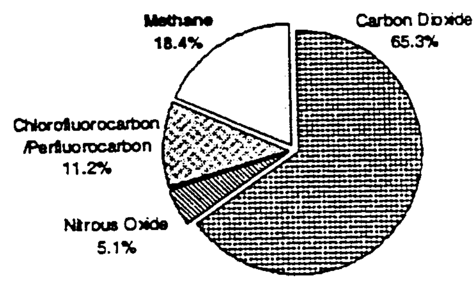
Reduced pollution threat.

Accelerated waste decomposition reduces the time over which high strength leachate and landfill gas will be generated. Recirculating leachate back through the landfill, which is practiced in the Yolo County Project, also reduces the pollutant content of leachate by using the landfill as a biological treatment system. Reaching the cessation of landfill gas generation and high strength leachate production while environmental protection systems are still relatively new will reduce the pollution threat from landfills.

Landfill life extension.

Landfill decomposition results in the conversion of biodegradable solid waste into gas, thereby creating additional landfill space. In conventional landfills this settlement usually occurs after landfill closure and these landfills lose the opportunity to translate the reduction in landfilled waste into extended landfill life. Settlement that occurs after landfill closure becomes a maintenance expense due to the need to continually place soil on the landfill to maintain slopes necessary for surface drainage. Accelerating landfill decomposition could reasonably be expected to extend landfill life up to 15% by placing additional waste on the temporary or intermediate soil cover before the landfill closure and placement of the final membrane cover.

Figure 2. Greenhouse Gases Contributors to Global Warming



Accelerated reclamation schedule.
A concept that goes hand in hand with controlled landfilling is one in which landfilling operations are cycled between multiple cells after decomposition. The idea is that landfill cells could be constructed for organic waste material and controlled landfilling would be applied to these cells to decompose, or treat the waste. Material from cells in which waste has decomposed could be excavated and used for beneficial uses, such as compost. Accelerated decomposition would allow for an accelerated timetable for landfill excavation and reuse.

Reduced post-closure maintenance.
Landfills are mandated to be monitored and maintained for at least 30 years following closure. Accelerated decomposition can significantly reduce costs for operation and maintenance of landfill gas control systems, leachate treatment, and final cap system. Beneficial end uses of the landfill site could also be implemented sooner.

Reduction of greenhouse gas emissions.
The release of greenhouse gas emissions is reduced both by higher recovery rates of landfill gas and from offsetting fossil fuel use with landfill gas energy. Methane, which comprises about 50-60% of landfill gas volume, is about 24.5 times more potent (mass per mass) as a greenhouse gas than carbon dioxide. Controlled landfilling also eliminates fugitive emissions beyond the 30-year post-closure period.

Standard Landfill Practices and Regulations - Risks and Opportunities
Sanitary landfilling is the dominant municipal solid waste disposal route in the U. S. with about 150 million tons of waste landfilled annually (U. S. EPA, 1990). Wastes are received at landfills and then spread, compacted, and covered at the end of each day with a thin layer of soil or other cover material until a planned depth is reached. Wastes are then covered with final cover, which until recently has normally been clay. Plastic membranes are coming into increasing use as a final surface cover and may be a requirement for future U. S. landfills (Federal Register, June 26, 1992). Surface membrane coverage, though significantly improving landfill gas collection efficiency, still further slows decomposition by retarding moisture infiltration (Leskiewicz, 1995; Kraemer, 1995). In addition, landfills are now mandated to have more secure base containment incorporating both clay and plastic liners.

"Present regulations result in retardation of biological activity, because waste remains dry."

"Full containment and restriction of liquid infiltration simply causes the waste to decompose more slowly, less completely, and less predictably."

Although regulations have mandated increasingly more secure containment of landfilled waste in the U. S., there is no regulation requiring management of biological conditions within the landfilled waste. In fact, the present regulations result in retardation of biological activity, because waste remains dry. The apparent effect is to "entomb" the waste, and such fully contained landfills are often referred to as "dry tombs" (Lee, 1990). Unfortunately, it has been found that no matter what measures are taken, "as is" waste will continue to decompose. The full containment and restriction of liquid infiltration simply causes the waste to decompose more slowly, less completely, and less predictably.

Decomposition of waste can pose problems associated with the generation of landfill gas and high strength leachate, but it also provides significant opportunity for energy applications when economics of energy production are favorable. In the U. S. only about 10% of landfill gas is now used for energy (Thorneloe, S.A., et al, 1997). A variety of regulations are in place that mandate the collection and destruction of the gas, usually by flaring. These regulations were initially adopted to address the hazards posed by offsite migration of the gas and pollutant emissions in air quality management regions (beginning with the Los Angeles basin). More recently, revisions to the Federal Clean Air Act as modified (Federal Register, May 30, 1991 et. seq.) have been the overriding drive for landfill gas collection in the U. S.. As applied now to landfills, this regulation mandates gas collection from all landfills exceeding a lower size limit of 2.75 million tons of waste in place and measured pollutant emissions of 55 U. S. tons per year (Federal Register, 1996). Estimates are that 60-70% of U. S. landfilled waste meet criteria necessitating gas collection (Walsh, J.J., 1997; Hill, 1996).

An additional consideration is that much of the landfill gas that will ultimately be produced will likely be generated over the very long time by a "dry", slowly decomposing landfill. This is a phenomenon referred to as "tailing" of production. Regulations in the U. S. generally mandate gas collection for 30 years following landfill closure, but significant quantities of gas may still be generated after the 30-year post-closure period. The surface emission criteria may not require collection of slowly generated gas because it may not surpass the minimum emissions threshold requiring collection. Landfill gas generated during the long-term tailing of production would not be recovered at all, let alone used to produce energy. With plastic membranes currently becoming common for final landfill cover, as much as 40-50% of landfill gas could be generated beyond the mandated 30-year post-closure maintenance period (Augenstein, D.A., et al, 1996). Much of this long-term gas generation is likely to escape to the atmosphere, thereby contributing to greenhouse emissions.

"Controlled landfilling results in the ability to make far more reliable projections of gas generation over time, reducing the financial risk involved in making sizable investments in energy equipment."

Prior to making an investment in equipment to utilize the energy potential of landfill gas, methane must be recoverable with sufficient predictability and reliability to justify the investment. Because of poor reliability for projections of landfill gas generation from conventional landfills, energy facilities are often undersized, or they are not pursued at all. Controlled landfilling makes the landfill environment much more conducive to microbial activity, accelerating waste decomposition and landfill gas generation. This results in the ability to make far more reliable projections of gas generation over time, reducing the financial risk involved in making sizable investments in energy equipment.

Another phenomenon that is occurring in the field of solid waste management is the regionalization of landfills. Because of the high cost of environmental protection for landfills, economies of scale result in significant benefits to larger landfills. These economic benefits support a trend toward larger, regional landfills for which gas generation rates would be more likely to require gas recovery systems and render energy uses as a feasible alternative. For landfills that are already required to install landfill gas collection systems, controlled landfilling would greatly improve the chances that energy uses will be economically viable.

Project Objectives

Objectives of Yolo County's Controlled Landfill Project are to:

1. Demonstrate substantially accelerated landfill gas generation and biological stabilization while maximizing landfill gas capture.
2. Monitor the biological conditions within the landfill cells.
3. Demonstrate that the recirculation of leachate is an effective leachate treatment strategy.
4. Estimate landfill life extension that can be realized through the rapid conversion of landfilled solids to gas and liquid.
5. Provide regulatory agencies with information that can be used to develop guidelines for the application of the technology.

6. Better understand the movement of moisture through landfills.
7. Assess the performance characteristics of shredded tires as a medium for the transfer of landfill gas to collection points.

Project Set-up

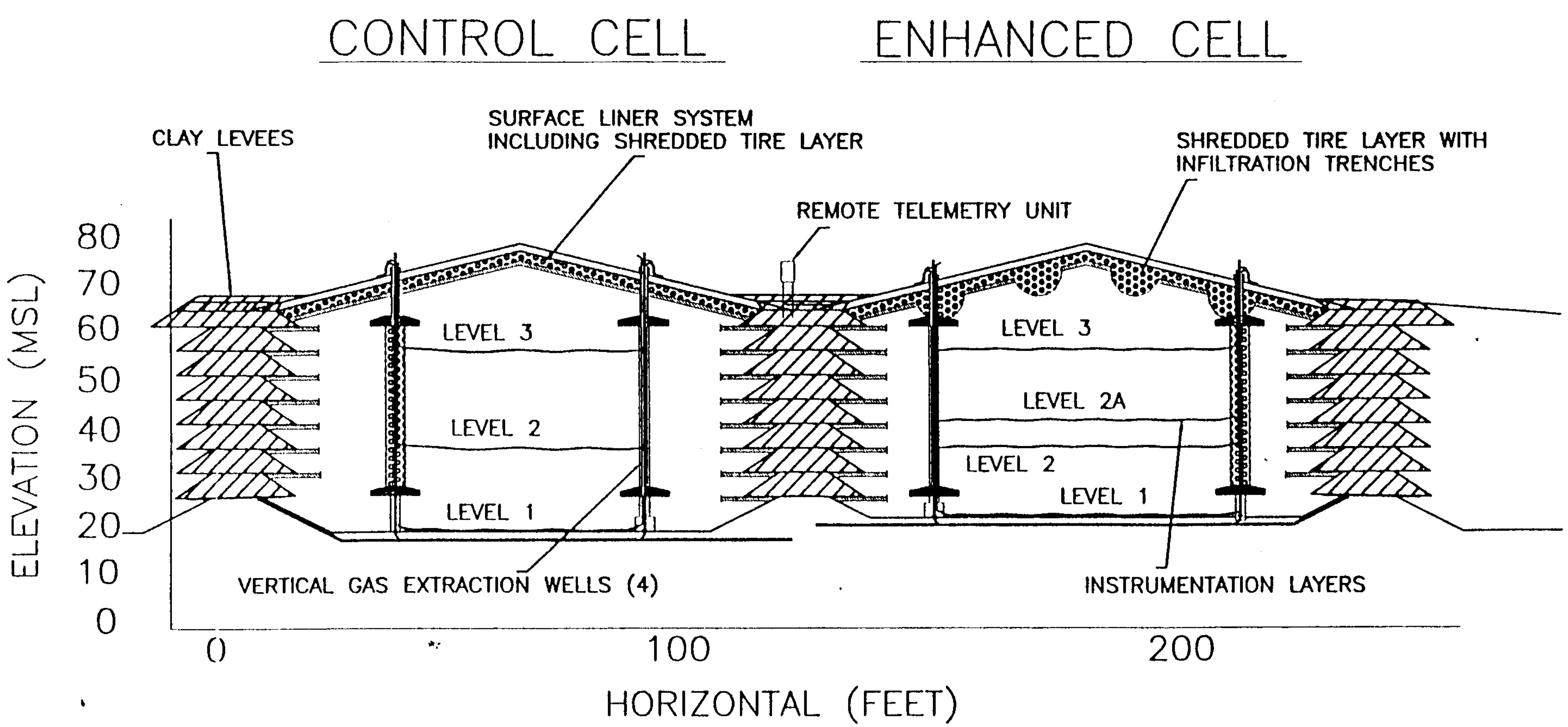
To demonstrate the benefits of controlled landfilling, Yolo County designed, built and operated two test demonstration cells. These cells are large enough to duplicate the compaction, heat transfer and other characteristics of large-scale landfilling at normal waste depth. The demonstration cells are surrounded by waste in the larger landfill module. The cell design and operation were purposely chosen so that they could be easily applied at sites around the U. S.. One cell serves as a control cell to represent a conventional landfill, while the other cell receives controlled additions of liquid, both water and leachate. The cell that is receiving liquid additions is called the "enhanced" cell. Each demonstration cell has an area of about 100 x 100 feet with an average depth of about 40 feet. Both cells were built with composite liner systems (soil and plastic liners) as mandated for environmental protection. This lining system essentially duplicates that of the larger landfill module. For the enhanced cell, an additional base lining is emplaced beneath the primary lining to satisfy California's regulatory constraints. The additional base liner allows detection of any leaks that may occur through the primary lining. The enhanced cell's double liner system consists of two liner systems, one built on top of the other. Both cells are completely sealed by compacted clay levees surrounding their perimeters. Plastic surface liners were also placed on each cell. Each completely sealed cell allows all liquid or gas inputs and outputs to be measured.

Each cell was filled with about 9,000 tons of curbside municipal solid waste from April to October 1995. Temperature and moisture sensors were placed at different levels inside both cells during filling. There are three instrumentation levels in the control cell and four in the enhanced cell. A total of 56 moisture sensors (two types) and 24 temperature sensors were placed in the two cells. The sensors are connected to a datalogger which records the sensor readings at set time intervals and allows remote downloading of the data to the main office through a remote telemetry unit.

All gas and liquid entering or leaving each cell is collected and measured separately. For collection of landfill gas each cell has two vertical landfill gas extraction wells and a horizontal "blanket" layer of shredded tires about two feet thick over the entire surface of the waste. The vertical wells are similar to gas extraction wells used in conventional landfills, but the blanket layer of shredded tires is an innovative design for gas collection that had not been used before. The concept is to have a high permeability layer on the surface of the landfill, like a layer of shredded tires, covered with an impermeable plastic liner. Landfill gas that rises to the surface is trapped under the surface liner and conveyed through the shredded tire layer to a collection point. A vacuum is applied at the collection point to extract the landfill gas. Shredded tires are also used in two of the four vertical gas wells with gravel used in the other two. The purpose of using shredded tires is to demonstrate their performance as a landfill gas extraction medium, and possibly as another beneficial end use for waste tires.

Liquid addition to the enhanced cell is accomplished by evenly distributing liquid to the fourteen infiltration trenches dug in the surface of the cell. The liquid is pumped to the infiltration trenches from a manhole which also receives leachate that drains from the enhanced cell. To increase the moisture content of the waste, supplemental liquid had to be added to the cell. The supplemental liquid is clean water from a groundwater pumping system located at the landfill site. The addition of supplemental liquid to the waste resulted in the generation of leachate which was subsequently recirculated into the cell. A cross-sectional view of both cells is shown in Figure 3.

"One cell serves as a control cell to represent a conventional landfill, while the other cell receives controlled additions of liquid, both water and leachate."



LANDFILL BIOREACTOR DEMONSTRATION CELLS
CROSS SECTION

FIGURE 3

tails of the demonstration project (technical, construction, operation) were described in a recent report and symposium presentation (Augenstein, et. al., 1997).

Demonstration Cell Construction

Construction of the demonstration cells began in the summer of 1993 after $250,000 of match funding was secured from the California Energy Commission. Sacramento and Yolo Counties contributed $125,000 each for the construction phase. The California Integrated Waste Management Board contributed an additional $63,000 to support demonstration of the use of shredded tires in landfill gas collection systems. This $563,000 was sufficient to complete construction and waste placement in the two demonstration cells.

"A drainage layer is placed on top the plastic liner to allow the flow of leachate down the slope and into the leachate collection trench."

To reduce costs, the demonstration cells were constructed as part of a larger, 20-acre landfill module. The total area of the demonstration cells within this 20-acre module is about 0.6 acres. The 20-acre landfill module was constructed with a "composite liner system" which means that it consists of both a plastic membrane liner and a clay liner. Construction of such a liner system involves the placement and compaction of a clay liner that is at least two feet thick and compacted to have an extremely low permeability (< 10^{-7} centimeters per second). A plastic membrane liner made of high density polyethylene, a very sturdy material that resists chemical degradation, with a thickness of about 1/16th of an inch, is then placed over the clay layer. To drain leachate from the landfill, the liner system is sloped towards a trench with a leachate removal pipe. A drainage layer is placed on top of the plastic liner to allow the flow of leachate down the slope and into the leachate collection trench. This drainage layer is referred as a "geonet" and is shown being placed over the plastic membrane liner in Photo 1. A "geofilter" is then placed over the geonet. Geofilter is a felt-like material, about 1/4 inch thick, whose purpose is to prevent particles of garbage and soil from clogging the geonet and impeding leachate flow to the trench. To protect the liner system from damage, the geofilter is covered with a layer of soil one foot thick. When the protective layer is complete the landfill is ready to begin accepting waste.

The control cell base liner system was constructed with a composite liner system identical to the 20-acre landfill module. However, the enhanced cell was constructed with a double liner, meaning that two of the composite liner systems were constructed one on top of the other. The reason for this is that liquid additions to the landfilled waste were planned to accelerate decomposition, and regulators were concerned that this might increase the possibility of groundwater contamination. Constructing a double liner system doubles the construction costs.

To facilitate drainage from the demonstration cells, gravel was used for a portion of the protective layer over the liner system as shown in Photo 2. The levees enclosing the two cells and the protective layer can be also seen.

Photo 1. Placement of Geonet on the Base Liner

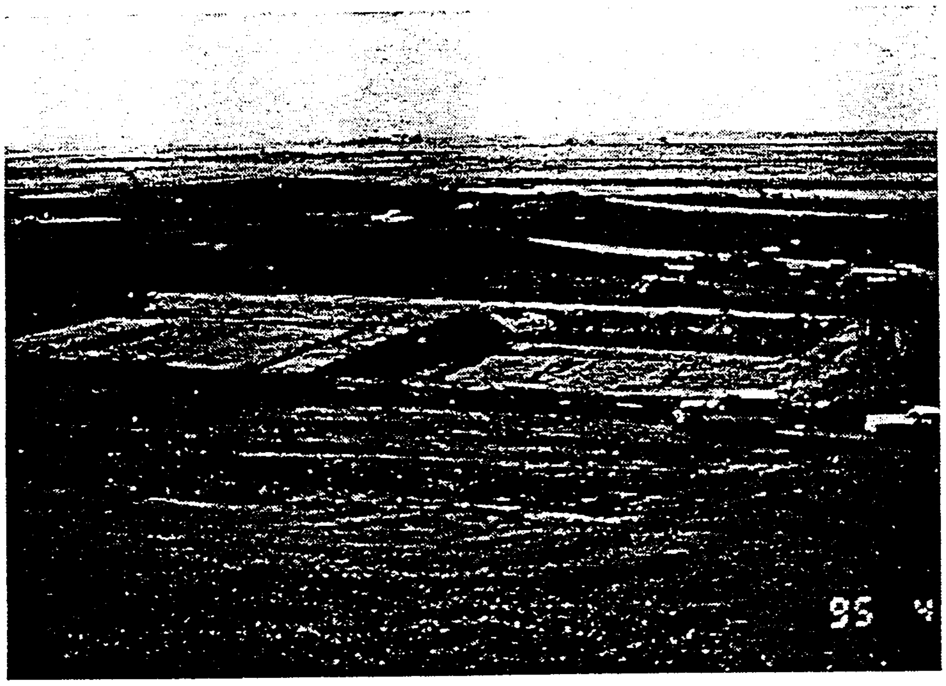


Photo 2. Gravel Drainage Layer

Waste was first placed in the demonstration cells in April 1995, and waste placement continued until October 1995. The waste placed in the demonstration cells was typical residential waste, the type of waste that is placed by families at the curb for pickup in packer trucks. Industrial waste and bulky items, like sofas and refrigerators, were excluded from the cells. The first "lift" of waste placed in the demonstration cells is shown in Photo 3. A lift is a layer of waste that is placed to a given height over an area before adding another lift. For instance, a landfill that is fifty feet deep might consist of five lifts of waste, each ten feet thick. The lifts in the demonstration cells were five feet thick, with nine lifts being placed to a depth of forty-five feet. At the end each day, waste that was placed is covered with "daily cover" to subdue odors, shed rainfall, and prevent animals and birds from getting into the waste. The soil at the Yolo County Landfill has a high clay content and would have created a barrier to liquid flow through the waste, so no soil was placed in the cells. Instead, shredded greenwaste was used as daily cover because it wouldn't impede the flow of liquid. Greenwaste is grass clippings and tree prunings that are brought to the landfill where they are shredded into a compost like material. The shredded greenwaste can be seen in Photo 3; the color of greenwaste is lighter than adjacent soil.

Clay levees, ten feet in thickness and five feet in height, were constructed around each cell to prevent migration of gas or leachate into or out of the cells (Photo 4). All gas or liquid entering or leaving each cell is collected and measured separately. Any exchange of gas or liquid from the cells with the surrounding waste in the larger landfill module would have confounded interpretation of the project results. The height of the levees was increased in five-foot increments. After placement of a lift of waste, the clay levee would be raised five feet, and waste would be placed both inside the cells and on the outside of the levee to provide support. This process was continued until the last lift of waste was placed.

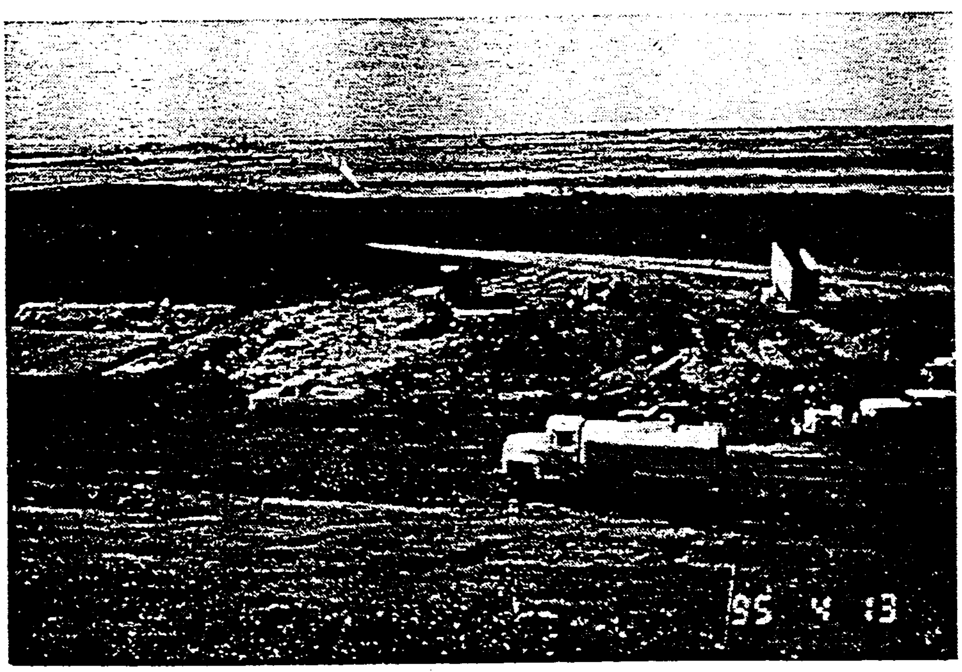


Photo 3. Placement of First Lift of Waste

Sensors were placed in the cells during filling to monitor temperature, moisture content, and gas pressure. Lessons were learned from previous projects in which instrumentation placed within landfills had not functioned. To prevent breakage of wires connecting the sensors, the lines were laid out in a meandering fashion to accommodate differential settlement of the waste mass. This is shown in Photo 5.

Photo 4. Clay Levees Surrounding Demonstration Cells

The final lift of waste was placed in a pyramid shape to facilitate drainage of rainwater, as shown in Photo 6, and covered with a layer of shredded greenwaste (Photo 7). Fourteen infiltration trenches were dug with a backhoe in the surface of the enhanced cell and filled with shredded tires for adding liquid to the waste. A distribution manifold delivers an equal flow of liquid to each trench.

About 500 tons of tires were used to construct a layer of shredded tires two feet thick on top of the last greenwaste layer on the surface of each cell (Photo 8). The shredded tire layer was placed on the greenwaste to serve as a "horizontal blanket" landfill gas collection layer. This type of layer is not normally constructed in landfills, but one of the goals of the project is to assess the performance of shredded tires in this type of application. In the foreground of Photo 8 is a white material; this is the geofilter- the felt-like fabric

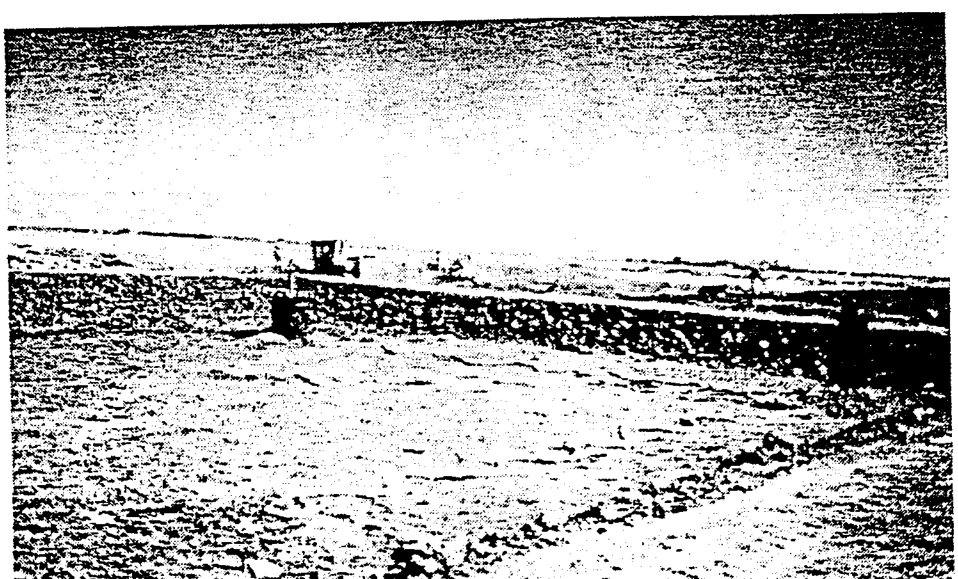


Photo 5. Sensor Instrumentation Lines

"Sensors were placed in the cells during filling to monitor temperature, moisture content, and gas pressure."

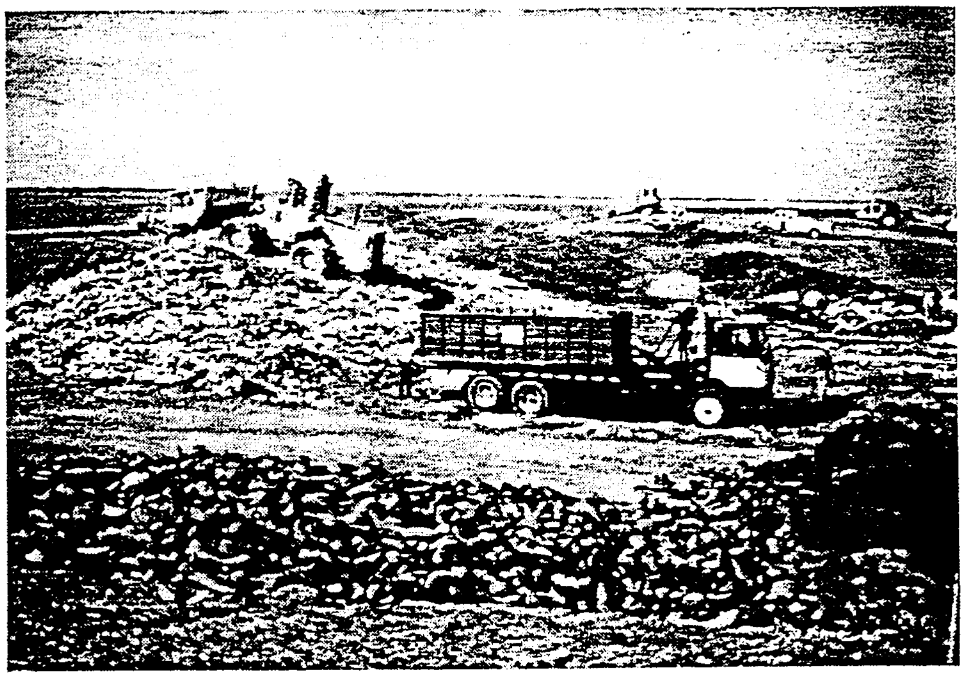


Photo 6. Placement of Final Lift of Waste

"To demonstrate the benefits of controlled landfilling, Yolo County has designed, built, and operated two demonstration cells large enough to duplicate the compaction, heat transfer and other characteristics of large-scale landfilling."

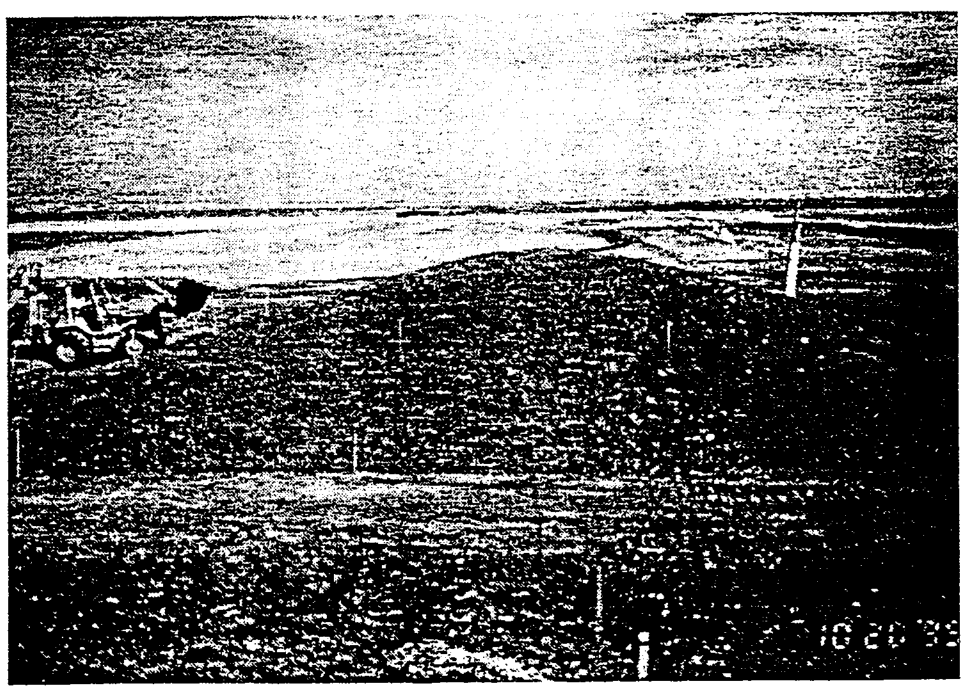


Photo 7. Layer of Shredded Greenwaste

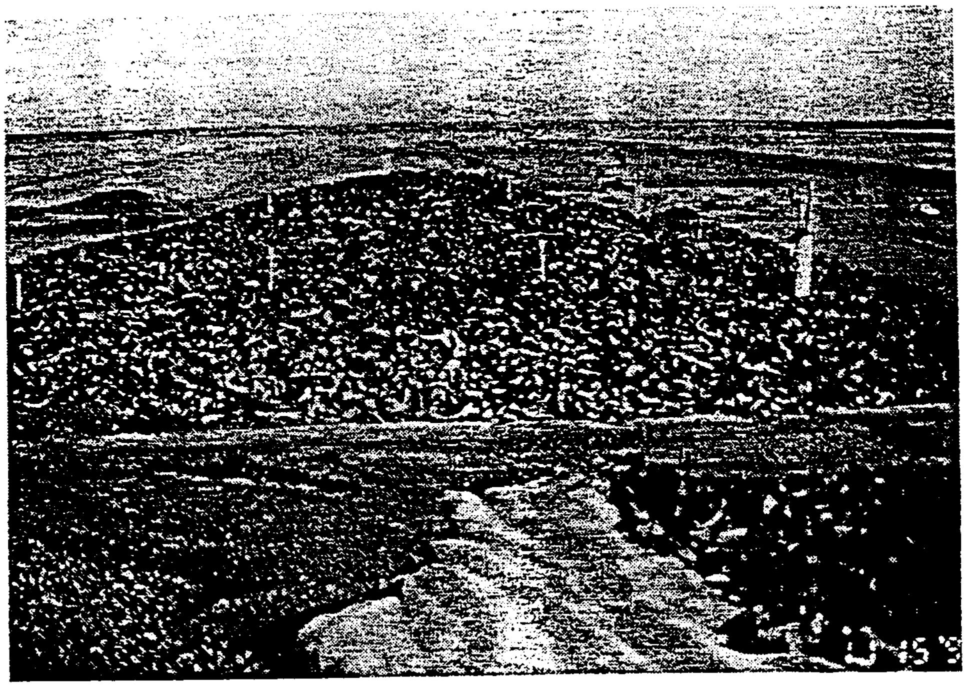


Photo 8. Layer of Shredded Tires (geofilter shown in the foreground)

"About 500 tons of tires were used to construct a layer of shredded tires two-feet thick on top of the last greenwaste layer on the surface of each cell."

"The shredded tire layer was placed on the greenwaste to serve as a "horizontal blanket" landfill gas collection layer."

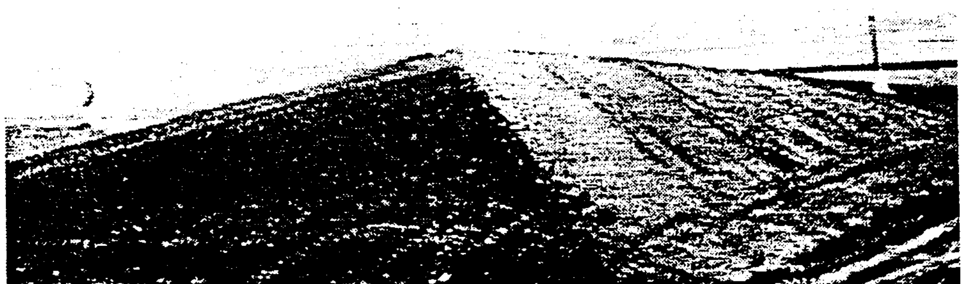


Photo 9. Final Grading of the Soil Layer

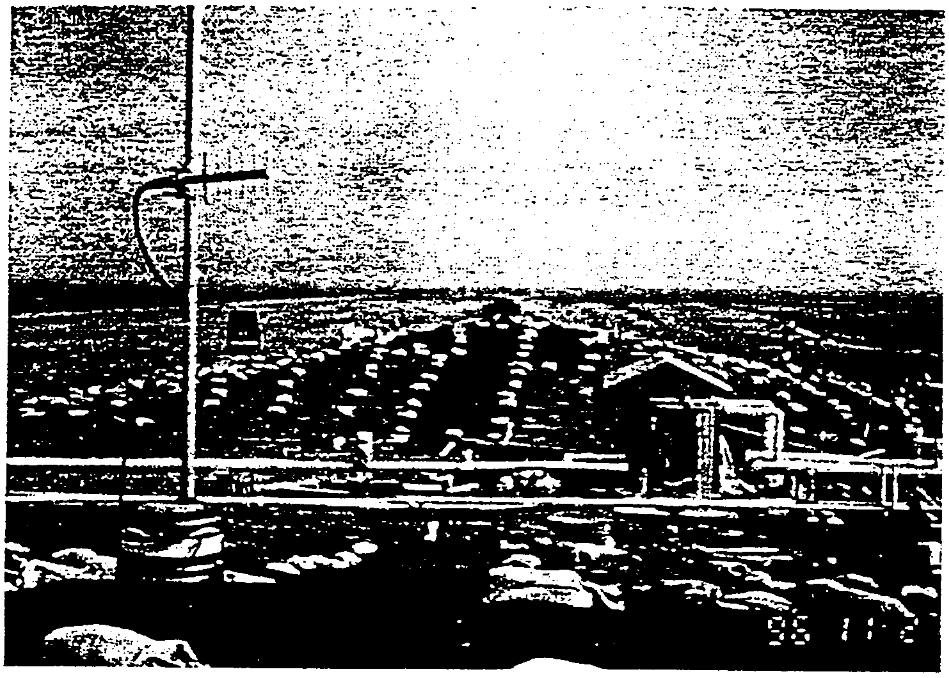


Photo 10. The Enhanced Cell with Plastic Membrane Liner

described earlier. Geofilter was placed over the shredded tire layer. to prevent the migration of soil particles that could clog the voids in the shredded tires. A one-foot thick layer of soil was placed over the geofilter (Photo 9), and plastic membrane liner was placed over the soil in November 1995. The plastic membrane liner on the surface of the cells prevents the escape of landfill gas (Photo 10). In this photo sandbags can be seen weighing down the plastic liner as well as the black geotextile walkways. The white pipelines are landfill gas collection lines and the antenna in the foreground is used to transmit data to a computer in the County office about 3 miles away. The shed houses the datalogger used to download data from the in-waste sensors and the remote telemetry unit for data transmission.

Construction of the gas measurement and leachate addition equipment was completed in June 1996, and the landfill gas collection vacuum was applied to the demonstration cells in October 1996. The addition of liquid began about a week following the application of the vacuum.

Major Tasks - Methodology

A comprehensive monitoring program was implemented to evaluate project performance. This program is divided into separate tasks, all of which are related to waste decomposition and landfill gas generation. The following is a list of the major project tasks.

1. Liquid Addition and Leachate Management
2. Leachate Analysis
3. Landfill Gas Composition and Flowrates
4. Landfill Settlement
5. Monitoring of Waste Temperature and Moisture
6. Shredded Tire Utilization
7. Data Management

1. Liquid Addition and Leachate Management

Garbage was placed in the cells during the dry season when no rain or moisture could enter the cells without being measured. This was also to ensure that liquid addition to the enhanced cell and the enhancement processes would start when desired, after the landfill gas collection system was ready. After the gas collection system was completed on October 16, 1996, liquid addition to the enhanced cell began on October 23, 1996. The addition of supplemental liquid to the enhanced cell was necessary to "jump start" the enhancement process in the relatively dry garbage.

The goal of liquid addition is to bring the moisture content of the waste up to field capacity. Field capacity can be thought of as the amount of water that can be absorbed by the waste without draining, like a sponge that soaks up all the liquid it can hold without dripping. Determination of when field capacity has been reached in waste is difficult because garbage is not a uniform material. Liquid can flow through preferential channels in the waste without wetting the whole mass. Therefore, it was necessary to develop a criterion to determine this elusive parameter. It was arbitrarily decided to add liquid until the daily volume of leachate was 50% of the liquid added. The supplemental liquid would then be shut off and only leachate would be recirculated through the enhanced cell. In principle, if the leachate volume stays the same or increases, then field capacity has been reached. However, if the leachate volume decreases then the waste is still absorbing liquid and field capacity has not yet been reached. This determination is actually a little less straightforward than it appears, because the leachate volume could stay the same simply because it is following flowpaths that are at field capacity while bypassing other areas of the waste that remain dry. Currently, several hundred gallons per day of leachate continue to be recirculated and the amount in recirculation is remaining relatively constant. No further liquid additions are planned for the near future as the enhanced cell appears to be sufficiently "enhanced", since it is generating substantially more landfill gas than the control cell.

2. Leachate Analysis

Leachate samples are collected from both the control and the enhanced cell. Samples are analyzed for standard water quality parameters. Leachate analysis provides information as to the dominant microbial population and stage of waste decomposition, and also provides information to assess the potential for leachate treatment. During the initial phase of waste decomposition, leachate carries a high pollutant load. However, when methane generation begins in earnest, pollutant levels drop drastically. Using leachate recirculation to improve leachate quality could provide a significant savings to many landfill owners who discharge their leachate to waste water treatment plants.

Leachate chemical analyses were performed weekly for the first two months of supplemental liquid addition. Close attention was paid to leachate chemistry and appearance during supplemental liquid addition. Following the termination of supplemental liquid addition, the sampling frequency was reduced to once every two weeks until one year had passed since supplemental liquid was first added. Leachate chemical analyses are currently being performed on a quarterly basis.

3. Landfill Gas Composition and Flow Rates

Landfill gas energy potential is based on the gas flow rate and the methane percentage. Higher landfill gas flowrates and methane percentages translate to higher energy content. Landfill gas from each cell is metered separately and gas composition is determined using a portable gas chromatograph. Gas composition is also used to check for leaks in the gas collection pipeline and the surface liner covering both cells. Since a vacuum is applied to the gas collection system, air can be drawn into the system through leaks. Air is mostly nitrogen and oxygen, but nitrogen is the best indicator of a leak in the system because oxygen can be removed by facultative bacteria that can live in either aerobic or anaerobic conditions. A leak can be localized and repaired by taking samples at different points in the gas collection system.

"Using leachate recirculation to improve leachate quality could provide a significant savings to many landfill owners who discharge their leachate to waste waster treatment plants."

4. Landfill Settlement

Extension of landfill life and the associated cost savings is an important benefit of controlled landfilling. To estimate the amount of landfill space created, periodic settlement surveys are performed for both cells. Changes in the surface elevations are tracked using settlement markers installed during the cell's construction. Comparison between settlement results of the control and enhanced cell are used to estimate the potential for landfill life extension.

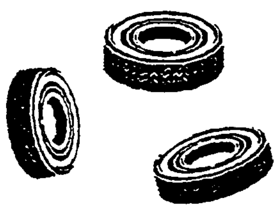
5. Monitoring of Waste Temperature and Moisture

Waste temperature and moisture are two parameters interrelated to bacterial activity and methane generation. Methane production has been shown to be strongly correlated to waste temperature; at temperatures above 55° Celsius methane generation can be inhibited, and optimum temperature is between 40 and 50° Celsius (Hartz and Ham, 1982).

A goal of the liquid management strategy is to uniformly distribute the liquid throughout the waste. The location of the moisture sensors allows monitoring of moisture movement both laterally and vertically within the waste. As liquid is added to the enhanced cell, moisture sensors indicate the movement of this wetting front. Two types of moisture sensors are used; a gypsum block moisture sensors and PVC moisture sensors. Gypsum blocks are commonly used in agricultural applications to track soil moisture for irrigation guidance. Due to the corrosive environment within the landfill, the gypsum blocks and temperature sensors are encased in plaster-of-paris to extend their life. PVC moisture sensors were designed by Yolo County staff and consist of a perforated PVC pipe (polyvinyl chloride) filled with gravel with two embedded electrodes to measure the presence of free liquid. The combination of two types of moisture sensors allow relative changes in the moisture content to be monitored throughout the project. The number of temperature and moisture sensors placed in the cells are listed in Table 1. More sensors were placed in the enhanced than the control cell because of the desire to monitor moisture movement from the addition of liquid taking place in the enhanced cell.

TABLE 1. Number of Temperature and Moisture Sensors in Demonstration Cells

Number of Sensors	Enhanced Cell	Control Cell
Temperature Sensors	13	11
Gypsum Block Moisture Sensors	25	15
PVC Moisture Sensors	12	4



"The use of shredded tires as a gas collection medium is a promising new market based on their low cost, constructablility and performance."

6. Shredded Tire Utilization

The California Integrated Waste Management Board (CIWMB) provided funding to the project to investigate the use of shredded waste tires in landfill gas collection systems. The disposal of waste tires is a problem in California, as well as many other states. The CIWMB is seeking to develop markets for waste tires to clean up the many waste tire piles throughout the state and to provide a use for the 28 million waste tires generated each year in California alone. As part of the project objectives, the use of shredded waste tires as an alternative gas collection media is being demonstrated. Roughly 500 tons of shredded tires (50,000 tires) were used to construct two horizontal and two vertical gas collection systems in the demonstration cells. Standard construction equipment was used in the construction of the gas collection systems without any major complications. Based on gas flow rate and pressure tests, shredded tire performance is comparable to gravel, the typical media used for this application. The use of shredded tires as a gas collection medium is a promising new market based on their low cost, constructablility and performance.

7. Data Management

Data from the instrumentation placed in the cells is collected automatically and stored in a datalogger in a control panel located at the project site. Data is downloaded from the office, located about 3 miles from the project site, at programmed intervals using a remote telemetry unit. A database has been setup to manage the collected data.

Partners Roles

This project was first envisioned in the late 1980's and a feasibility study was conducted whose favorable results led to efforts to secure funding to do a field-scale project at the Yolo County Landfill. The California Energy Commission offers research contracts through their Energy Technologies Advancement Program, and funding proposals were submitted in 1989, 1990, and 1991, until the third proposal was finally awarded funding. EMCON Associates, an engineering consulting firm, supported the preparation of the proposals in 1990 and 1991. John Pacey, former CEO of EMCON, has continued to provide technical guidance to Yolo County staff since the project's inception.

Don Augenstein, currently working with the nonprofit organization *Institute for Environmental Management* (IEM), prepared the proposals while at EMCON. Mr. Augenstein has continued to work with Yolo County on the project since leaving EMCON to form IEM in 1992. Mr. Augenstein has contributed significantly to all phases of the contract, thanks to his 25 years of experience working in the field of biomass-energy.

Financial contributors to the construction phase of the project, other than Yolo County, were the California Energy Commission, Sacramento County, and the California Integrated Waste Management Board. These contributors have provided not only funding but oversight regarding the aspects of the project that they were supporting. The California Energy Commission supported the project on the basis of the energy potential of the technology and environmental benefits. Sacramento County, which operates a landfill of its own, is interested in the landfill operational benefits and potential for energy generation at their landfill. The California Integrated Waste Management Board sponsored a study of shredded waste tire use in landfill gas collection systems to promote new markets for used tires.

The U. S. Department of Energy, through Public Technology Incorporated's Urban Consortium Energy Task Force (UCETF), and the Western Regional Biomass Energy Program (WRBEP), provided funding for the operations and monitoring phase of the project which began in September, 1996. The Electric Power Research Institute, which is managing the WRBEP contract with Yolo County, and the UCETF have provided guidance and oversight on the monitoring phase of the project. Also, the UCETF holds periodic meetings at which projects receive peer review by professionals from other jurisdictions who are working on projects of a similar nature.

III. Technology Transfer

"Yolo County Controlled Landfill Demonstration Project is currently the only one of its kind in the world, and has attracted a lot of attention and visitors, both nationally and internationally."

Because the Yolo County Controlled Landfill Demonstration Project is currently the only one of its kind in the world, it has attracted a lot of attention and visitors, both nationally and internationally. In August of this year, the Solid Waste Association of North America held a conference in Sacramento, California. Bioreactor landfills were one of the principal topics at the conference, which concluded with a tour of the Yolo County Project. Both the California Integrated Waste Management Board and the California Water Resources Control Board have held seminars at the Yolo County Landfill to educate agency staff on controlled landfilling. Staff from the U. S. Environmental Protection Agency have also visited the site for tours of the project.

International visitors to tour the site have included officials from the Netherlands, Denmark, United Kingdom, Thailand, Japan, India, and Korea. Tours are also routinely given to industry professionals and classes from neighboring universities. Additionally, over the past year Yolo County staff have presented three papers at solid waste conferences based on data from this project. We also routinely respond to requests for information from colleagues in the solid waste industry.

IV. Results

The results presented here are preliminary, as liquid addition to the enhanced cell began on October 23, 1996, a little more than one year ago. Ideally, the project will continue to be monitored at least until the end of landfill gas generation from the enhanced cell, which is expected to be at least five years. Results to date are very encouraging; landfill gas generation from the enhanced cell is considerably greater than from the control cell, and other results have verified the anticipated benefits. Since the data are still preliminary, further study is planned to evaluate the technology. Results for the following components of the monitoring program are discussed in this section.

- Landfill Gas Generation and Capture
- Leachate Chemical Characteristics
- Hydraulic Characteristics
- Waste Absorptive Capacity
- Moisture Distribution
- Waste Temperature
- Landfill Settlement
- Shredded Tire Performance

Landfill Gas Generation and Capture

The landfill gas collection and metering system was completed in June 1996, and landfill gas from each of the two cells has been metered separately since that time. Before the start of liquid addition to the enhanced cell, the landfill gas generation rate was about the same for each cell, but two months after the start of liquid addition, the gas flow rates from both cells increased dramatically. During this period, the gas flow rate from the control cell increased from 9 to 20 standard cubic feet per minute (scfm) and the enhanced cell increased from 9 to 40 scfm, double the control cell. The reason for the increase in gas flow from the control cell is not clear, but it may simply be a function of the natural development of the bacterial population.

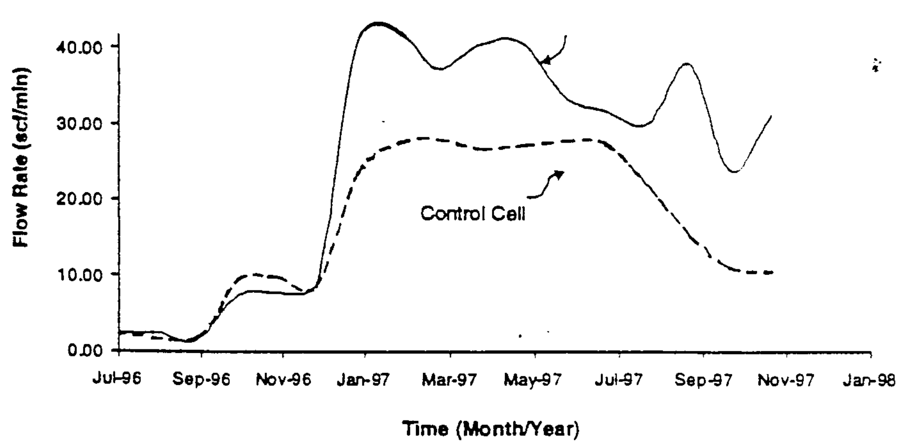


Figure 4. Average Monthly Landfill Gas Flow Rates

Overall, the enhanced cell has produced 30% more landfill gas than the control cell since June, 1996. From July to September 1997, landfill gas flow rates for the control cell have decreased from 22 to 11 scfm. This is attributed to a decreasing bacterial population resulting from drying of the waste in the control cell. Moisture is removed from the cell in landfill gas, which exits the cell saturated with moisture. The microbes use water in the generation of landfill gas, which also contributes to drying of the waste over time. Also, the readily biodegradable waste will breakdown sooner and more rapidly than slowly biodegradable waste, resulting in decreasing gas production over time.

The enhanced cell gas production has fluctuated slightly, but currently is at 31 scfm. The peak flow from the enhanced cell was 42 scfm and occurred in January, 1997, and for the control cell it was 29 scfm in February of 1997. A graph of the flowrates from both cells is shown in Figure 4. The ultimate yield of landfill gas, or the total amount of landfill gas produced from typical municipal solid waste, is estimated at about 3.5 ft^3/dry pound (Moore, 1994). The amount of landfill gas generated by each cell is shown in Table 2. The cumulative total landfill gas generation curve for each cell is shown in Figure 5. Thus far, the enhanced cell has generated 37% of its ultimate expected yield and the control cell has generated 25%.

The energy potential of landfill gas is a function of its methane content, which is typically presented as a percentage of landfill gas volume. Methane percentages have been fairly consistent and not significantly different between the two cells (Table 2). Thus far, it does not appear that controlled landfilling has increased the energy potential of the landfill gas, only its flowrate.

TABLE 2. Summary of Landfill Gas Generation

Parameter	Control Cell	Enhanced Cell	Enhanced Benefit
Total Landfill Gas Volume	0.878 scf/dry lb.	1.31 scf/dry lb.	0.432 scf/dry lb. (33% increase)
Average Gas Flow Rate - 1997 only	22 scf/min	36 scf/min	14 scf/min higher (38% increase)
Average Methane Percentage - 1997 only	51%	53%	comparable (2% higher)

Leachate Chemical Characteristics

When waste decomposes anaerobically, an equilibrium is reached between several interrelated microbial groups. At the onset of methanogenesis, the development of this equilibrium relationship can be tracked through observations of leachate chemistry. Simply put, cellulosic material is first broken down into sugars. The sugars are then broken down into organic acids, resulting in an increase in acidity which is reflected in a decreasing pH. This stage of the decomposition process is referred to as the "acid phase" and is reflected in the results for day 44 in Table 3. During the acid phase the pollutant load of leachate rises dramatically due to the high organic acid content and components that become soluble in the low pH environment. The organic acids are transformed into methane and carbon dioxide by "methanogens", the bacterial population responsible for methane formation. As the methanogenic population increases and organic acids are removed, the pH rises to around neutral (pH 7 is neutral) and pollutant levels drop. These changes in leachate chemistry for the enhanced cell are shown in Table 3, where the dramatic increase in pollutant content corresponding to the low pH conditions can be readily seen. The control cell has not produced an appreciable amount of leachate; therefore, leachate analysis for the control cell was discontinued to save the sampling budget for analysis of the enhanced cell.

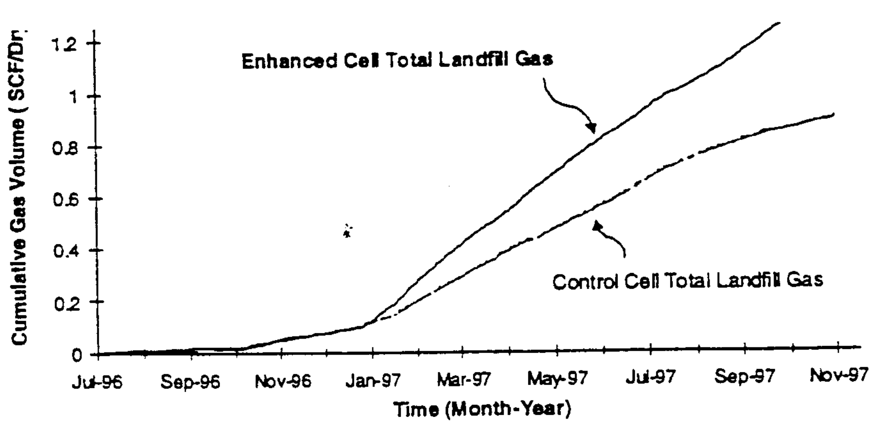


Figure 5. Cumulative Total Landfill Gas

TABLE 3. Enhanced Cell Leachate Data Corresponding to the Number of Days Following the Start of Liquid Addition

PARAMETER ANALYZED	Day 27 11/19/96	Day 44 12/6/96	Day 93 1/24/97	Day 273 7/23/97
pH	7.6	5.8	8.5	7.09
Chemical Oxygen Demand	31.9 mg O/L	20300	5920	2770
Total Dissoved Solids	1100 mg/L	19800	9650	6700
Total Organic Carbon	9.8 mg/L	9830	1150	850
Total Kjeldahl Nitrogen	4.0 mg/L	673	518	385
Iron	<17 ug/L	152000	933	4
Manganese	4900 ug/L	41900	4000	18
Calcium	86 mg/L	1400	480	239
Toluene	<0.5 ug/L	160	75	71

During the first 34 days of liquid addition and leachate recirculation, there was no significant change in the leachate quality. However, on Day 35, the leachate color turned from a light orange to black and the odor was much stronger than it had previously been. Field analysis of pH was done and it was found to have dropped to 5.65. The results of a laboratory analysis done on Day 44 showed that the pH level was still low, as shown in Table 3. By Day 93 the methanogens were established and the pH had risen back to neutral.

Hydraulic Characteristics

Based on observations of leachate quantity and characteristics, some important conclusions can be made regarding hydraulic characteristics. This information is important in scaling this technology up to full-scale landfills. Leachate flow through landfills can be divided into two portions, channeled flow and macroscopic flow. *Channeled flow* occurs when leachate finds flowpaths allowing it to flow relatively rapidly through the waste. Channeled flow is in contrast to macroscopic flow which is liquid that is absorbed by the landfill and percolates through the waste as more liquid is added. *Macroscopic flow* is analogous to dripping water on a sponge until the sponge finally starts to drip. Channeled flow is analogous to liquid that would move more rapidly through a tear or hole in the sponge. The volume of channeled flow is estimated in this study to be 17% of the liquid that infiltrates the landfill. For instance, for a given volume that infiltrates the landfill, 17% will flow rapidly through the waste while the remaining 83% will soak in and move slowly through the waste.

"Information on landfill hydraulic characteristics generated by this project is important in scaling this technology up to full-scale landfills."

Permeability is the rate at which leachate flows through the landfill. This parameter corresponds to the macroscopic flow described in the previous paragraph rather than the channeled flow. The permeability of waste is estimated in this study to be 1.1 ft/day, or 3.9 x 10^{-4} centimeters per second.

V. Project Benefits

Controlled landfilling technology provides a number of benefits, not only in terms of increasing landfill gas energy generation, but also in reducing landfill environmental impacts and providing landfill operations benefits. The benefits of this technology are discussed below.

Increase in Landfill Gas Energy Use from Controlled Landfilling

Present landfill gas use for energy in the U. S. is about 10% of its potential (Thorneloe, S.A., et al, 1997). Most landfill gas energy is electric generation. Statistics are incomplete, but based on experience, this usage probably takes place at landfills receiving about 20% of U. S. waste and generating 20% of U. S. methane. From these landfills, only about half the gas is used for energy because of fugitive emissions to the atmosphere and conservative undersizing of energy equipment. Controlled landfilling could greatly increase U. S. landfill gas energy for several reasons including:

- Accelerated gas generation rate from given waste over a shorter time frame
- Higher fractional gas recovery (less fugitive emissions)
- Better estimates of energy availability for equipment requirements
- Improved economics for energy uses at normally marginal landfills
- Better economies of scale for greater-capacity energy equipment

Recognizing uncertainties, it is nonetheless possible to make some projections as to additional energy that might be produced from controlled landfilling if practiced in the U. S.. It is assumed that energy markets, particularly for renewable electricity generation, are favorable. For electricity, this implies the sale price for renewable electricity (as opposed to conventional fossil) to electric grids would on the order of 5 cents per kWh; typically it is on the order of 2.5-3 cents. A sale price of 5 cents per kWh has been demonstrated necessary to support wood-fired and wind-powered generation, the principal renewables in most U. S. states. Such sale prices for renewable electricity could come about either as the result of state restructuring, or nationwide, from overriding federal legislation requiring minimum renewable energy purchases by utilities.

The basic assumptions used in this analysis to estimate U. S. primary energy or electricity potential from controlled landfilling are explained below:

"Present landfill gas use for energy in the U.S. is about 10% of its potential."

- The U. S. landfilling rate is estimated at slightly over 150 million tons per year (U. S. EPA).
- Controlled landfilling is applied at landfills receiving 60% of U. S. waste, or 90 million tons per year.
- Methane yield = 1.8 cubic feet per pound of dry waste (3600 cubic feet per ton). This figure is in the upper range of what is attainable from a conventional landfill and is a reasonable expectation for controlled landfilling.
- Energy content of landfill methane is 1,000 Btu per cubic foot.
- The heat factor for conversion of Btu's to kWh's is 10,000 Btu per kWh. This heat rate is attainable with newer internal combustion (IC) engine/generator sets. More efficient fuel cells may ultimately permit 30-40% more power than IC engines.
- Up to 5% of methane may be lost within six months to one year after waste is placed but before landfill cover is applied (Vogt and Augenstein, 1997).
- Energy equipment is down for repairs or service 5% of the time.
- 90% of generated methane recovered (other than the losses) is used for electricity production.

Waste Absorptive Capacity
It is important to have reliable information on waste absorptive capacity because adding liquid beyond the absorptive capacity of the waste can result in ponding of leachate in the base of the landfill, increasing the risk of groundwater contamination. The absorptive capacity appears to be about 45 gallons per ton of "as-placed" waste. "As-placed" waste, or waste at the time that it is landfilled, contains moisture, typically about 20-25% of its weight. Therefore, 100 pounds of "as-placed" waste contains about 80 pounds of waste and 20 pounds of moisture. In this study, the waste absorbed an additional 45 gallons of liquid per ton of waste after being landfilled.

Most of the supplemental liquid addition (87% of the total) occurred between October 23, 1996, and January 2, 1997. As of January, 1997, the daily volume of leachate was approximately 50% of the liquid input per day. Supplemental liquid was then shut off but leachate continued to be recirculated. The waste continued to absorb the leachate, so supplemental liquid was added on a few occasions after January. As of April 1997, no more supplemental liquid has been added and only leachate is being recirculated. A total of 377,690 gallons of supplemental liquid was added to the enhanced cell and a graph of the cumulative liquid volumes is shown in Figure 6. After the last day of supplemental liquid addition, the daily volume of leachate generated has steadily decreased from 2,000 to 260 gallons per day. This is an indication that the waste is still absorbing the recirculated leachate and field capacity may not yet have been attained.

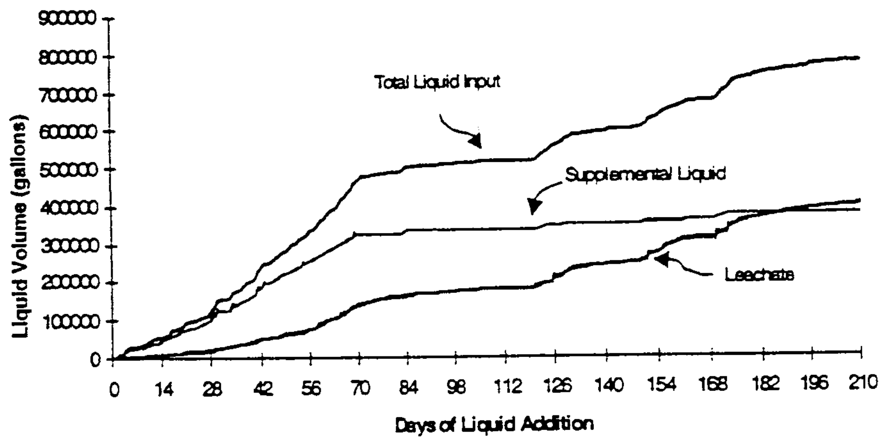


Figure 6. Cumulative Liquid Volumes Versus Time

Moisture Distribution
In general, liquid was distributed fairly uniformly within the waste. Sensors placed closest to infiltration trenches were the first to record increases in moisture content and, as liquid addition continued, lower levels also increased in moisture content. Within each level, sensors placed on the south side of the cell increased in moisture sooner than the north side. The vertical gas collection wells are located on the south side and the waste in this area may have been compacted less than in other areas due to concerns that the wells might be damaged. The applied vacuum at the gas collection wells may have also contributed to the migration of moisture toward this area.

Waste Temperature
Temperatures within both cells exhibited the same basic pattern before liquid was added to the enhanced cell. Then, at the start of liquid addition, the temperature in the enhanced cell dropped sharply. This was due to the addition of cool, supplemental liquid, which had a temperature of about 66°F (19°C). As the cool liquid moved down through the cell, temperature sensors recorded drops in temperature at the same time that moisture sensors showed increases in moisture contents. After their initial drop, temperatures in the enhanced cell have been slowly rising and are currently at an average of about 45°C. Interestingly, temperatures at the south side of the enhanced cell are about 5°C higher than on the north side. This may be related to the same factors that affected the north-south distribution of liquid previously described. Temperatures in the control cell have decreased steadily and are at an average of about 38 °C.

"Increased settlement is a major benefit of this technology due to the potential for landfill life extension."

Waste Settlement

Increased settlement is a major benefit of this technology due to the potential for landfill life extension. Periodic surveys of surface elevations are performed as part of the monitoring program. Settlement results cover a 17-month period which includes 12 months of liquid addition and leachate recirculation to the enhanced cell. The control cell settled an average of 9 inches and the enhanced cell 29 inches, about three times that of the control cell. The increased settlement is attributed to accelerated decomposition and the increase in waste weight due to the addition of liquid. The potential for extending landfill life by applying this technology would appear to be significant.

Shredded Tires as a Gas Collection Media

The use of shredded tires as a landfill gas collection media was evaluated as part of this project. Shredded tires worked as well or better than conventional gravel media, actually allowing better gas flow due to the greater porosity of shredded tires. The performance of the shredded tire layer as a dual system for landfill gas collection and liquid addition is a promising system for full scale applications.

Difficulties Encountered

Operating a sealed system that allows no air infiltration and no losses of landfill gas has proven to be a challenge. Because the system is completely sealed, the only way for gas to exit the cells is under the influence of the applied vacuum. This has resulted in the need for intensive monitoring of the cells, because in the event of a considerable change in the vacuum, or the vacuum is shut off for some reason, the plastic membrane surface liners can balloon and could possibly tear.

Landfill gas generated from the demonstration cells is conveyed to a landfill gas-energy facility at the landfill. A vacuum is created at the facility that is applied to the entire landfill to recover landfill gas, not just to the demonstration cells. Being part of an overall system, the vacuum at the demonstration cells is subject to changes when other parts of the system are adjusted, such as a generator being shut down for service at the energy facility. If the vacuum gets too high at the demonstration cells, air can be pulled in to the gas recovery system, apparently increasing the amount of gas generated. This is adjusted for by monitoring the amount of nitrogen and oxygen in the landfill gas, and correcting the measured gas volumes for air infiltration.

The leachate drainage system in the enhanced cell has not operated as anticipated. Leachate depth in the base of the cell is monitored at the lowest point in the cell, in the leachate collection trench just where the drainage pipe exists in the cell. Liquid has been observed to build up in the trench until it reaches a depth of about 20 inches, and then drains rapidly from the cell. This cycle was periodic, with leachate building up to a depth of 20 inches, draining, and repeating the process. After the addition of supplemental liquid was stopped in April, 1997, the leachate flow rate dropped, and after falling below 800 gallons per day, this buildup of liquid stopped occurring and the cell has since drained with no buildup. It is surmised that the method of construction, designed to prevent the entry of air or the escape of landfill gas, allowed a vapor lock to form in the drain pipe that caused this phenomenon.

The surface of each demonstration cell was constructed in the shape of a pyramid to facilitate rainfall runoff as the surface of the cells settled. In spite of this, the surface of the enhanced cell has settled so much that it was necessary to place soil on the cell to prevent ponding from rainfall. Alternative designs could have been used during construction to better shed runoff over the longer-term of the project.

Based on the above assumptions, the total primary energy generated is 2.9×10^{14} Btu/yr, which can produce 3300 megawatts of electrical energy. Reducing this by 10% to account for landfill gas energy already produced, the increase in electrical energy from controlled landfilling could amount to 3,000 megawatts, enough electricity to continually meet the needs of a population of about 2 million Americans. This calculation serves to illustrate the welcome addition to renewable energy and electricity supplies that would result from wide scale application of controlled landfilling.

Greenhouse Gas Mitigation Potential from Controlled Landfilling

The benefit from mitigation of greenhouse gas emissions from controlled landfilling is significant. Not only does controlled landfilling reduce emissions from landfills, but it also offsets fossil fuel energy generation with the production of electricity from landfill gas. To estimate the reduction in methane emissions from landfills practicing controlled landfilling, two situations are considered. Together, the waste in these two categories total 90 million tons as was assumed in calculating the U.S. energy potential. The two categories of landfills are:

1. Those *landfills requiring controls* by size or volatile organic compound (VOC) emission criteria. Landfills for which this situation applies are assumed to receive a total of 70 million tons of waste.
2. Those *landfills not requiring controls* under present criteria but find energy uses from controlled landfilling attractive. The landfills in this category that would otherwise be emitters are assumed to receive 20 million tons of waste.

Assumptions used to estimate greenhouse gas abatement potential are explained below:

- For *conventional landfills* methane is assumed generated at 1.4 cubic feet per dry pound of waste; for *controlled landfilling* the yield is assumed to be 1.8 cubic feet.
- The conversion from volume methane to tons of methane (@ 60 °F) is 47,429 ft^3 of methane per ton (American Gas Association).
- The accepted value of methane's global warming potential used by the Intergovernmental Panel on Climate Change (IPCC) is 24.5-fold that of CO_2 on a mass basis.

"Not only does controlled landfilling reduce emissions from landfills, but it also offsets fossil fuel energy generation with the production of electricity from landfill gas."

Greenhouse gas abatement from controlled landfilling (resulting solely from increased efficiency of landfill gas collection) is estimated at 40 million tons of carbon dioxide equivalent emissions. This is arrived at by taking the sum of what would have been emitted without controlled landfilling minus emissions that still occur even when controlled landfilling is applied. Fossil fuel offsets are estimated at about 30 million tons of carbon dioxide equivalent, for a total greenhouse gas mitigation of 70 million tons of carbon dioxide equivalents. An explanation of calculations follows.

Landfills requiring controls

As previously mentioned, it is assumed that with *conventional operations* less than 5% of total methane will be generated before final cover is applied to the landfill. It is further assumed that the next 70% of methane is generated during the "extraction phase" while an extraction system is active and is collecting at 90% efficiency. The final 25% of methane is generated after 30 years or more, in the "tailing" phase, and escapes to the atmosphere. Altogether, with conventional operation about 37% of methane generated escapes from such landfills into the atmosphere, which is equivalent to about 29 million tons of carbon dioxide annually.

Landfills not requiring controls
This second category of landfills includes both those with a total design capacity below 2.5 million megagrams of waste (2.75 million U. S. tons), and those with a total design capacity over 2.75 million tons but that require no landfill gas controls because VOC emissions are below the threshold. Many of these large "VOC-clean" landfills are now being documented with capacities of up to 5 million tons or more (Walsh, 1997, Hill, 1996). Controlled landfilling may be applied to many of these to realize energy recovery. Even landfills with less than 2.75 million tons of waste have substantial energy potential; each million tons of waste represents about 35 megawatt-years of power generation. For these landfills, the recovery of methane changes from zero, since recovery is not required, to 90% when controlled landfilling is applied (minus the 10% that escapes before the landfill is covered and collection inefficiency). The methane emissions resulting from these landfills not required to have collection systems are equivalent to another 29 million tons of carbon dioxide per year.

Landfills practicing controlled landfilling
When controlled landfilling is applied, collection of landfill gas is assumed to be 95% efficient. The combination of a membrane cover and application of vacuum to a permeable layer creates an efficient collection system with essentially zero emissions. Also gas generation is completed in 10 or fewer years so no gas is lost due to tailing of production. The only gas emitted is the 5% (or less) generated before the membrane cover is placed and the 5% that is lost during the landfill gas collection period. Therefore, the methane emissions that result from controlled landfills containing 90 million tons of waste is equivalent to about 18 million tons of carbon dioxide.

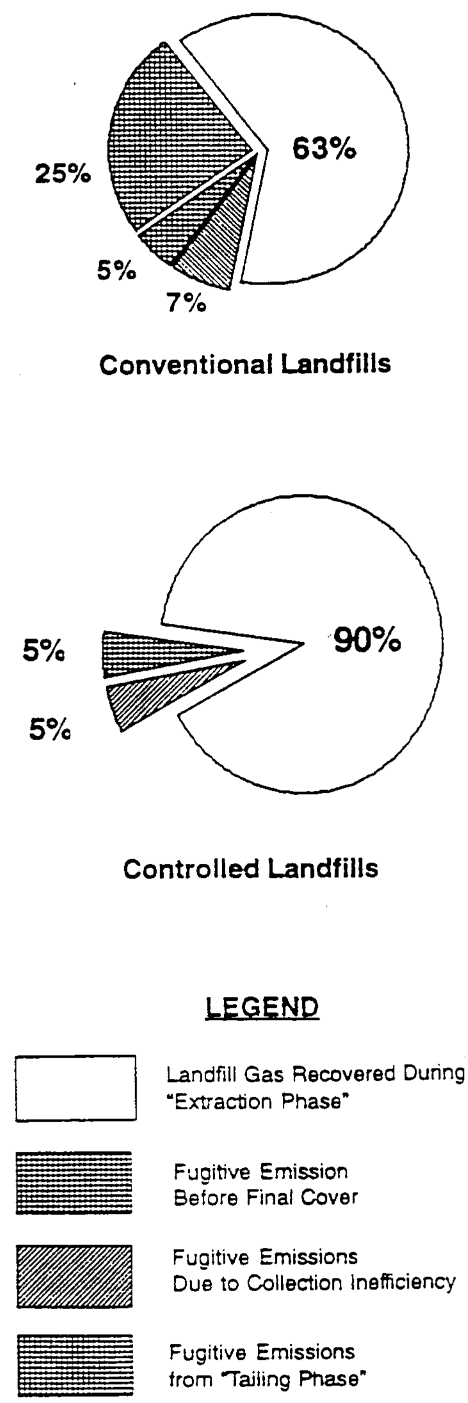
Emissions abatement from fossil fuel offsets
The final factor in greenhouse gas abatement is the fossil CO_2 displaced (the "swing" fuel is nearly always fossil that is displaced by a renewable). With generation divided between natural gas and coal, fossil fuels' average hydrogen to carbon ratios approximate that of oil. Therefore, oil is used to represent the displaced fossil fuel in these calculations. The carbon dioxide emission abatement is calculated to be roughly 29 million tons. The constants used in the analysis are the following:

- 1 barrel of oil = 6,000,000 Btu
- Heat factor for landfill gas energy = 10,000,000 Btu per megawatt-hour
- 5 barrels of oil = 1 ton of oil
- 1 ton of oil contains about 1,700 lbs. of carbon

Cost Effectiveness of Methane Mitigation through Controlled Landfilling
When options are being evaluated to reduce greenhouse gas generation, a range of costs per ton of carbon dioxide equivalent abatement can be developed. The common sense approach is to target those methods of greenhouse gas mitigation that achieve the largest reduction in emissions for the lowest price. Controlled landfilling gives low-cost greenhouse gas emission reductions, as is shown in the following example using electricity generation as the basis.

As an initial observation, it should be noted that a sufficiently favorable sale price for landfill gas derived electricity would result in achieving these greenhouse gas reductions at zero or even negative cost. This would be true providing the sale price of renewable electricity to the grid is sufficiently high, such that the associated greenhouse gas abatement would be obtained at a profit. However, renewable energy oftentimes cannot compete with conventional energy sources such as fossil fuels or hydroelectricity, and a premium sale price has been necessary to support renewable energy. Something akin to this is now being termed "greenpower", where utility customers choose to pay slightly more for their energy

Figure 7. Landfill Gas Recovery and Fugitive Emissions



Leachate treatment costs are directly tied to the pollutant load, which can be dramatically reduced by recirculating the leachate through the landfill, an integral part of controlled landfilling. Recirculating the leachate through the landfill gives the microbes additional opportunities to remove pollutants from the leachate and generate more methane. This cost savings is not estimated here as it can vary significantly depending on treatment plant requirements, but the savings is significant and reduces the likelihood of treatment plant upsets and groundwater contamination from high strength leachate.

Status of Commercialization

The Yolo project is only the second field-scale demonstration project to combine enhancement with gas capture; the first occurred in Mountain View, California, in the 1980's. Perhaps most importantly, it is the first demonstration project showing high controllability of enhancement and for which the results, over the first year, are highly favorable in terms of both continuity of acceleration and completeness of gas capture. Thus, with favorable results recently evident, the possible applications are only now being considered. Yolo County itself will apply the technology provided the economics are favorable. Another landfill owner who has announced the intention to apply the technology is the Rabanco Corporation of Roosevelt, in Washington. Rabanco operates a 3000 ton/day landfill in the dry region of Washington State east of the Cascade range.

Obstacles to Commercialization of Controlled Landfilling

Controlled landfilling is moving slowly towards commercialization for two primary reasons, economic and regulatory obstacles. Some of these obstacles are barriers to the generation of landfill gas energy, while others pertain to the implementation of controlled landfilling. If landfill gas is not used for energy, it is typically flared, and the environmental benefits associated with landfill gas energy production are not realized.

Barriers to Landfill Gas Energy Production

As described in previous sections, renewable energy in general, including landfill gas derived energy, cannot compete with conventional fuels such as fossil or hydroelectric in an open market. As discussed previously, renewable energy typically requires a premium sale cost of 1.5 to 2.5 cents per kWh above conventional fuels. Several mechanisms that could be used for realizing the environmental benefits of renewable energy are listed below (Augenstein, 1997).

- Voluntary programs such as "green" renewable power purchases at a premium price.
- Simple premiums provided for renewable energy sale price which could take the form of tax credits.
- Minimum renewable energy purchase requirements for utilities.
- A surcharge in which conventional energy sold is taxed to support renewable energy.
- A 'carbon tax", which is a levy based on fossil fuel emitted in the form of CO_2 or its equivalent.

Obtaining the necessary permits to operate a landfill gas-energy facility can be problematic, particularly in areas classified as non-attainment for certain air pollutants. Internal combustion engines, the most commonly used landfill gas-energy technology, are reliable and effective energy generating devices. However, the extreme heat and pressure of an internal combustion engine can cause increases in emissions of certain pollutants, particularly NOx. Increases in these emissions can lead to requirements that emissions offsets be purchased to operate the facility, which may render some projects non-economically viable.

"The Yolo project is the first demonstration project showing high controllability of enhancement and for which the results, over the first year, are highly favorable in terms of both continuity of acceleration and completeness of gas capture."

"Benefits to Controlled Landfilling include an increase in renewable energy resources, significant climate and other environmental benefits, and landfill operational benefits that could reduce the costs of solid waste management."

Barriers to the Implementation of Controlled Landfilling

Although not explicitly banned by Federal regulations, the addition of liquid to landfills constructed with standard composite liner systems is typically prohibited by regulators at the state level. For example, to add liquid to the demonstration cell used in this project, a double base liner system was required, effectively doubling the cost. The construction of double liner systems in full scale landfills would increase the cost of landfill construction to the point that revenue from energy generation and other benefits would not be sufficient to offset increased construction costs. The result is that waste disposal fees would have to be raised to finance the double liner system, and such an increase in disposal fees is typically infeasible. The solid waste industry is very competitive and those paying for disposal, such as cities or garbage haulers, are always looking for a better deal. It is likely that an increase in disposal fees at a landfill to fund non-mandated environmentally beneficial practices such as controlled landfilling would only result in the landfill going out of business because its wastestream would go to another, cheaper landfill. Even in an area where a landfill has no competition, the political pressure to maintain waste disposal fees as low as possible is intense.

Regulatory changes allowing controlled landfilling without a double liner system will highly depend on the landfill site. Sites where potential impact to the groundwater are low may be more suitable for single liner containment. While, sites with high groundwater levels, may still be required to have a double liner system. Placement of a double liner system is to ensure groundwater protection when adding liquid to landfills. However, as shown in this project, the rate of liquid addition in controlled landfilling can be adjusted to prevent ponding on the base liner system thereby minimizing a groundwater threat. The benefit of early decomposition of landfilled waste while the landfill liner is relatively new would actually reduce the long-term risk to groundwater due to the reduction in a leachate pollutant load. Ultimately, additional data on this technology will be needed to base decisions and allow single liner systems.

VI. Conclusions

Controlled landfilling, where landfills are operated as solid waste treatment systems rather than long-term solid waste storage units, has a number of significant benefits over conventional landfilling. Benefits to this technology include an increase in renewable energy resources, significant climate and other environmental benefits, and landfill operational benefits that could reduce the costs of solid waste management. This project is demonstrating that wetting landfilled waste can greatly accelerate the decomposition rate of waste, resulting in stabilization of the waste in five to ten years rather than several decades. The project has experienced no significant problems. It is accomplishing all project objectives and providing information important for the scale-up of the technology to full-scale landfills.

VII. Bibliography

Augenstein, D.A. (1997) *Economics, "Externalities", and Landfill Gas Energy*, Presented at the Sixth International Landfill Symposium, Sardinia, Italy, October 13-17.

Augenstein, D.A., R. Yazdani, R. Moore, and K. Dahl (1997). *Yolo County Controlled Landfill Demonstration Project*, Proceedings, Solid Waste Association of North America (SWANA), 20th Annual Landfill Gas Symposium, August, Monterey, California, pp.43-87.